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TOXICITY AND PERSISTENCE OF NEARSHORE SEDIMENT CONTAMINATION FOLLOWING THE 1991 GULF WAR

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In January 1991, the world's largest oil spill inundated extensive coastal areas of the Gulf with massive quantities of crude oil. In August 1993, the authors collected sediment samples from eleven beach sites at four tidal elevations in Kuwait and Saudi Arabia. Ten-day static sediment toxicity tests with the marine amphipod *Rhepoxynius abronius* revealed significant sediment toxicity (reduced survival) at five sites. Infrared spectrometry indicated that the highest concentrations of petroleum hydrocarbons occurred at these same five sites. Other variables such as ammonia concentration, silt and clay content, and total organic matter in the sediment had no affect on amphipod survival. Concentrations of petroleum hydrocarbons greater than about 1 mg g^{-1} dry sediment caused signifcant amphipod mortality. Such toxic sediment concentrations occurred at Al Khiran, Kuwait, and along an extensive coastal area of Saudi Arabia from Ras Tanajib to Abu Ali (a distance of over 100 km). The overall area of sediment toxicity corresponds closely to the spill trajectory and presence of sea surface petroleum as recorded on airborne radar soon after the spill (9 March 1991). These results indicate that sediment toxicity from the world's largest oil spill persisted for at least 30 months. Additionally, petroleum hydrocarbon concentrations in the sediments of contaminated sites were sufficiently high to cause continued leaching of oil to the sea-surface.

INTRODUCTION

The Gulf environment and petroleum

The Gulf is one of the most productive water bodies in the world. Clear, shallow water, warm temperatures, and an inflow of nutrients from the Tigris and Euphrates Rivers leads to thriving marine communities. Coral reefs, especially on the offshore islands, provide a substrate for many organisms and shelter for numerous fish (Basson et al. 1977). In addition, seagrasses, mudflats, and mangroves add to the overall productivity of the region, and fisheries represent a valuable resource for many of the Gulf countries (Basson et al. 1977; Price 1993). The enclosed and shallow nature of the Gulf (average depth of only 35 m) make it particularly subject to accumulation of anthropogenic contaminants. Because of the narrow exchange through the Strait of Hormuz into the Gulf of Oman, the time required for all Gulf water to come within the influence of the open sea is 2.4 y (Hunter 1983), or an actual flushing time of about 3 to 5.5 y (Sheppard 1993). Maintaining marine water quality in the Gulf is vital, not only to preserve these productive ecosystems, but also to protect seawater sources for coastal water desalination plants.

The Gulf suffers from chronic oil pollution associated with local exploration, exploitation, refining, routine handling, discharge of tanker ballast water as well as from natural seeps (Zarba et al. 1985). Sediments from Kuwait, collected at 66 locations between November 1979 and December 1980, had concentrations of petroleum hydrocarbons (mainly from anthropogenic sources) ranging from 1 to 291 $\mu g\ g^{-1}$ dry wt. Kuwait crude oil equivalents (Zarba et al. 1985). These data were collected before the 1983 Nowruz blowout (resulting from the hostilities between Iraq and Iran) which released about one-half million barrels (68 metric tonnes) of oil into the Gulf.

Spilled oil spreads, weathers, and sinks. Weathering includes the chemical and physical processes of evaporation, dissolution, vertical dispersion, emulsification, photochemical and biochemical degradation, and sedimentation (Karrick 1977; NRC 1985). Typically about 56% of spilled oil adsorbs to bottom sediments (Knap and Williams 1982) where oxidation processes are hindered (Blumer and Sass 1972). Thus, measurements of oil concentrations in marine sediments are generally more indicative of oil pollution than measurements in the water column.

High concentrations of oil in sediments negatively impact benthic communities. In general, the sensitive species die or relocate and oil tolerant opportunistic species fill the available niches, but there is a broad array of sublethal effects including those on reproduction and behavior (Snowden 1993). For example, littleneck clams exposed to oil burrow more slowly, or remain on the sediment surface and become vulnerable to greater predation from crabs (Pearson et al. 1981). Some shellfish can concentrate oil as high as 30 $mg\ g^{-1}$ dry wt of tissue and remain contaminated as long as the sediments in which they live retain oil (Howarth 1987). Negative impacts on the benthic community can affect fish populations that depend on the benthos for food.

The Gulf War spill

During the Gulf War, from 19-28 January 1991, oil was released from two major sources: three tankers anchored at Kuwait's port of Mina Al-Ahmadi, and the Mina Al-Ahmadi Sea Island terminal. The valves at the Al-Ahmadi terminal were opened on 22 January 1991, and discharged oil for 4 d. Five other tankers and several other terminals added more oil throughout the spring and early summer (Reynolds 1993). In total, approximately 6 million barrels (819 metric tonnes) of crude oil were released, resulting in the world's largest oil spill, an amount 20 to 30 times greater than the Prince William Sound Alaska spill of 1989. Approximately half the oil evaporated into the atmosphere and more than a million barrels (136 metric tonnes) were moved into large pits carved out of the desert (Earle 1991). The dominant wind pattern pushed the spill to the south. Between March and May 1991, about 905 thousand barrels (123 metric tonnes) of oil washed ashore along much of the coastline from Kuwait south to the Abu Ali peninsula, a hook of land which stopped the southern advance of the spill in Saudi Arabia (Fig. 1) (Earle 1991).

Impacts on the marine environment were most noticeable along the Saudi Arabian Coast where damage to critical coastal habitats in certain areas appeared irreversible (Readman et al. 1992; Fowler et al. 1993; Gerges 1993). Less damage occurred along the Kuwait, Iraqi and Iranian coasts, and the impact was almost below the level of detection in other offshore and coastal areas of the Gulf (Fowler et al. 1993; Gerges 1993). Coral reefs, seagrasses, and mangrove forests recovered relatively quickly in most cases. However, many intertidal communities remained affected by the oil spill and the depleted prawn stocks could be a result of reduced productivity (Mathews et al. 1993; Price et al. 1993).

In August 1991, a study was undertaken to assess the environmental impacts of the oil spill along the Gulf Coast of Saudi Arabia. The study included a semi-quantitative descriptive assessment of the impacts of oil and other anthropogenic disturbances, and involved chemical analyses of sediment, bivalve and fish tissues, and toxicity testing of sea-surface microlayer and near-surface seawater samples. In August 1992, the same sites were resampled, and other important areas in Saudi Arabia and Kuwait were included (Hardy et al. 1993). This second study focused on identifying areas

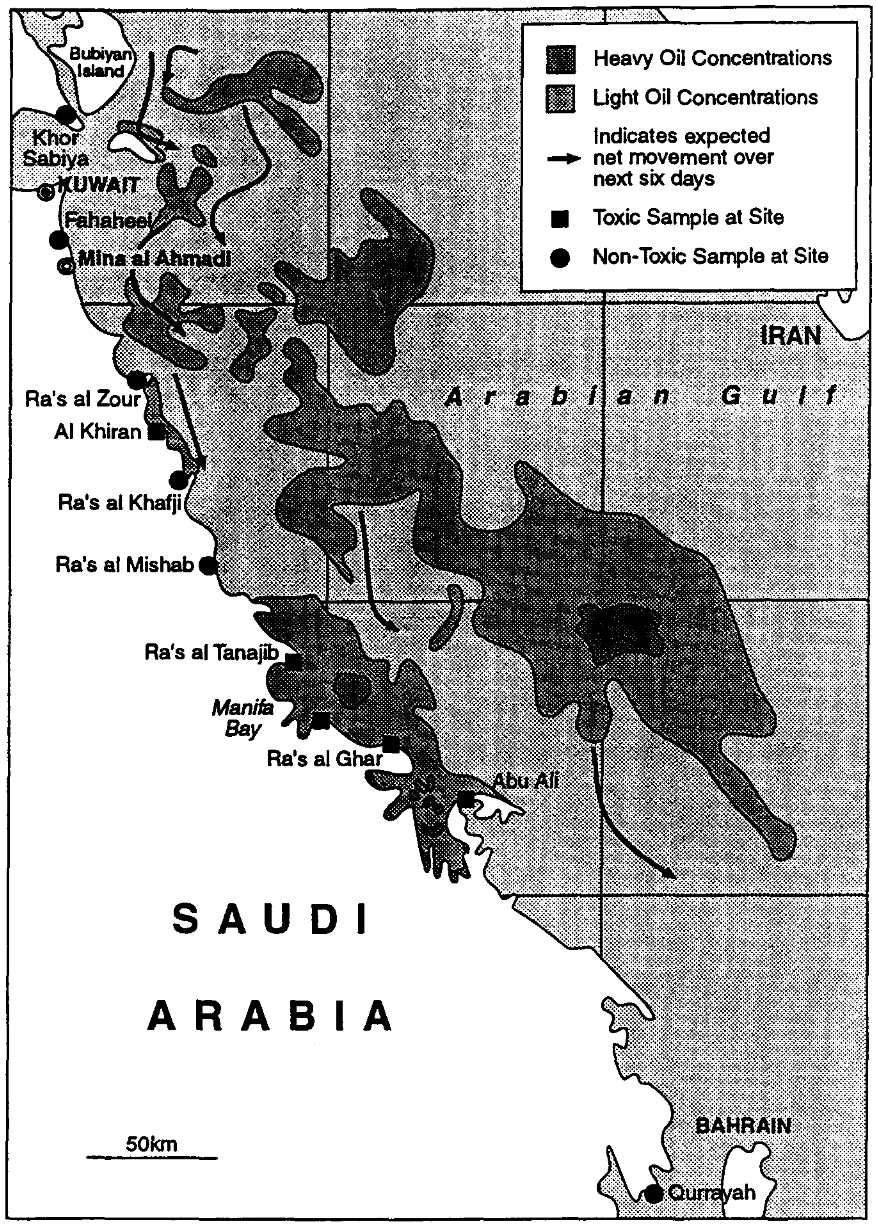

Fig. 1. Sample collection sites along the Gulf Coast. Shaded areas indicate the spatial distribution and trajectory of spilled oil on 9 March 1991, as measured by side-looking airborne radar by the U.S. Coast Guard. Heaviest oil concentrations occurred in the darkly shaded areas.

of nearshore sea-surface microlayer contamination and toxicity along the Gulf Coast of Kuwait and Saudi Arabia. Results suggested that slow leaching from nearshore sediments represented a long term source of toxic contamination to the sea-surface of the Gulf (Hardy et al. 1993; Price et al. 1994).

Although several studies have assessed nearshore sediment petroleum concentrations resulting from the Gulf War spill (Readman et al. 1992, 1996; Fowler et al. 1993), no other studies have directly examined the toxicity of these sediments to marine organisms. In August 1993, the authors collected sediments from 11 of the same sites sampled earlier in August 1992. They determined hydrocarbon and petroleum hydrocarbon concentrations and conducted a marine amphipod toxicity test to reveal locations where significant toxicity and contamination may have persisted two and a half years after the world's largest oil spill.

Objectives

The objectives of this study were to determine, 30 months after the oil spill: 1) concentrations of petroleum hydrocarbons in intertidal sediments; 2) toxicity of these sediments to a representative marine organism (the amphipod, *Rhepoxynius abronius*); and 3) the presence or absence of visible sea surface slicks leaching from intertidal sediments.

METHODS AND MATERIALS

Sample collection

During August 1993, the authors collected samples at 11 coastal sites from Khor Sabiya, Kuwait, to Abu Ali and Qurrayah, in Saudi Arabia (Fig. 1). At each site, four samples were collected along a transect perpendicular to the shoreline. At the time of sample collection, elevations were noted as: 1) high water mark; 2) middle of the wave wash zone; 3) 0.2 to 0.5 m depth; and 4) 1 m depth. Samples were collected using a 17 cm diameter, 6 cm long plexiglass tube, with a sample volume of 231 cm^3. Sediments were maintained at -20° ± 2°C, until they were thawed 11 months later for toxicity tests at the Battelle Marine Sciences Laboratory in Sequim, WA, USA.

Hydrocarbon concentrations

Total hydrocarbon concentrations were measured by infrared spectrophotometry of freon extracts of sediments using EPA Method 413.2 (EPA 1979). The petroleum hydrocarbon portion of the total hydrocarbons was then determined (EPA Method 418.1). Silica gel dessicant was added to the extract to eliminate the non-petroleum hydrocarbon portion (EPA 1979). Infrared spectrometry provided a detection limit for petroleum hydrocarbons of 17 $\mu g\ g^{-1}$ (SD ± 8.1) sediment.

Toxicity tests

In general, species used for toxicity tests should be available in large numbers, occur over an extended geographic range, represent important components of the ecosystem, and originate from, or represent, marine habitats similar to the contaminated site (NRC 1985). *Rhepoxynius abronius* is a free-burrowing amphipod that has been successfully used in sediment toxicity testing since the late 1970s (Swartz et al. 1985). Species of the genus *Rhepoxynius* are widely distributed on the west coast of North America and are also present on the east coast (Barnard and Barnard 1982). The large data base for the response of *R. abronius* to a variety of sediments and chemicals establishes its usefulness as a test species.

During 19-22 July 1994, over 6000 *Rhepoxynius abronius* were collected from West Beach on Whidbey Island, WA, using an infaunal dredge. The amphipods were sieved through a 1.0-mm mesh to remove predators. They were immediately transported in 28 L tubs, containing their native sediment and seawater, to the laboratory and placed in holding tanks with a flow-through seawater system. Water quality measures (temperature, pH, dissolved oxygen, and salinity) were checked daily. The amphipods were not fed before or during the test period.

Beginning 24 July 1994, toxicity tests were conducted following standard protocol guidelines described by the American Society For Testing and Materials (ASTM 1996) with minor modifications. Because of the relatively small size of the Gulf sediment samples, sediments were added to smaller jars (473 mL, filled to 300 mL with seawater) than those used in the standard protocol (1 L). However, the 2 cm depth required by the standard protocol was maintained and the smaller jars had no effect on amphipod survival (Randolph 1996). Also, to further reduce the amount of sediment needed for the toxicity test, replicates were reduced from 5 to 3. Five different concentrations of $CdCl_2$ (0, 0.5, 1.5, 3, and 4 mg $CdCl_2\ L^{-1}$) were used as a positive (toxic) control.

Results were analyzed statistically using Toxstat (1994). Trimmed Spearman-Karber Estimates of LC_{50} were applied to the positive (toxic) control. Initially, the toxicity test data were evaluated with the X-square test for normality. Tests also included analysis of variance, Shapiro-Wilk's test for normality, Hartley's test for homogeneity of variance, Bartlett's test for homogeneity of variance, and the Bonferroni t-test for mean comparison of treatments with a control using unequal numbers of replicates. Samples with 100% mean mortality have no variance, causing the applied statistics to deviate from their intended function. Therefore, statistical treatment was not applied to samples that killed all the amphipods (toxicity is explicit) or to samples with 5% or less mean mortality (an insignificant amount that would not statistically indicate toxicity).

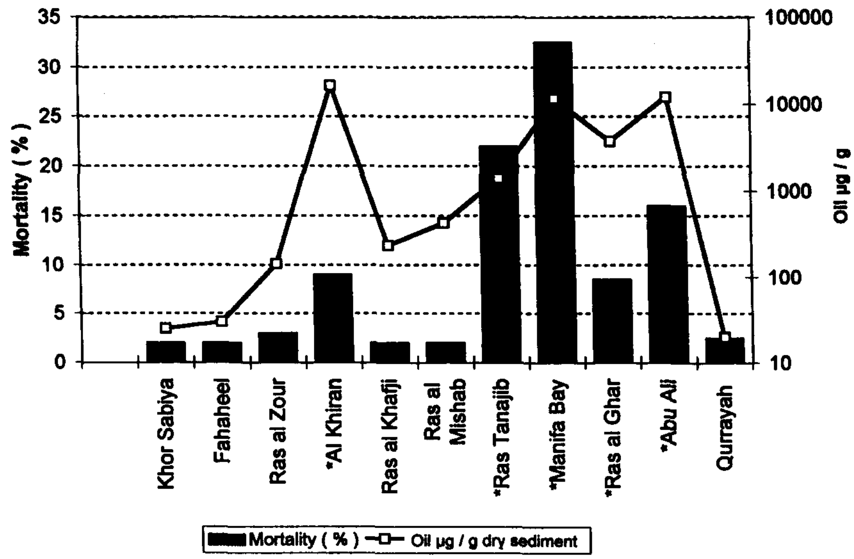

Fig. 2. Concentration of total petroleum hydrocarbons (site mean) from north (Khor Sabiya, Kuwait) to south (Qurrayah, Saudi Arabia) along the Gulf coastline. * = sites which included samples toxic to the marine amphipod *Rhepoxynius abronius*.

Other factors

Ammonia is toxic to infaunal species such as amphipods (Kohn et al. 1993). *Rhepoxynius abronius* has an LC_{50} of 78.7 mg L^{-1} ammonia. Test jars were set up for a two-week waiting period prior to initiation of the toxicity test, allowing bacteria to transform ammonia to the less toxic nitrate and nitrite forms. Overlying water was changed one time during the waiting period to reduce high ammonia concentrations that could affect amphipod survival. Aliquots of sea water were taken, one replicate daily, from the overlying water in the toxicity test jars. An ORION ammonia-specific electrode was used to measure ammonia in the aliquots.

Fine refers to material smaller than 63 µ and represents the silt and clay fraction of the sediment. Amphipod survival in fine uncontaminated field sediments (≥80% silt-clay) can be 15% lower than in native sediments (Dewitt et al. 1988). Since sediments were wet, and some were laden with oil, they were dried to a constant weight at 70 ± 2 °C, and the oil was removed by incineration at 550 °C for 1 h. Clean dry sediments were weighed and sieved through a 63 µm sieve. The fine portion was weighed and expressed as a percentage of the sediment's total dry weight.

Total organic matter was estimated as the percent weight loss after the ignition of dry sediment. Samples were dried to a constant weight at 70 ± 2 °C, incinerated at 550 °C for 1 h, and weighed again to determine the percent weight loss. Organic content is represented by the percent total volatile solids of dry sediment.

RESULTS

Hydrocarbon concentrations

Infrared spectrometry revealed petroleum hydrocarbons at all sites. The petroleum concentrations in the sediment varied between samples by several orders of magnitude, ranging from little to moderate to heavily-oiled (Table 1). The highest hydrocarbon concentrations occurred at Al Khiran, elevation 4 (1 m water depth), then Abu Ali, elevation 4, and Manifa Bay, elevations 1 and 2 (Table 1). Ras Tanajib, elevation 1, and Ras al Ghar, elevation 1, also had high hydrocarbon concentrations (Table 1). Sediments contained less petroleum hydrocarbons than total hydrocarbons. Sediment samples from five sites (Al Khiran, Ras Tanajib, Manifa Bay, Ras al Ghar, and Abu Ali) contained petroleum hydrocarbon concentrations greater than 1 mg g^{-1} dry sediment. At several sites, especially at Manifa Bay, surface oil slicks, apparently leaching from the beach sediments and extending offshore several hundred meters, were observed.

Toxicity tests

The 96-h positive toxic control test using cadmium chloride produced an LC_{50} of 1.7 mg L^{-1} for a 10% Trimmed Spearman-Karber Test, which falls within the acceptable range of 0.40 to 1.94 mg L^{-1} for *Rhepoxynius abronius*. Toxicity data passed the normality tests and homogeneity of variance tests.

Table 1. Characteristics and toxicity of Gulf nearshore sediments.

Site			Elevation *				
		1	2	3	4	Mean	S.D.
Khor Sabiya							
	% Mortality	2	3	0	2	2	1
	Max. NH3 concentration	<1	<1	<1	<1	<1	<1
	Petroleum hydrocarbons	0.00	0.01	0.00	0.00	0.00	0.00
	Total hydrocarbons	0.00	0.09	0.01	0.01	0.03	0.04
	% Fines	0.3	0.5	0.2	0.1	0.3	0.1
	Total organic matter	0.01	0.02	0.04	0.01	0.02	0.01
Fahaheel							
	% Mortality	0	5	2	2	2	2
	Max. NH3 concentration	<1	<1	2	3	2	1
	Petroleum hydrocarbons	0.00	0.08	0.02	0.02	0.03	0.03
	Total hydrocarbons	0.02	0.07	0.03	0.12	0.06	0.04
	% Fines	0.5	0.2	0.4	0.2	0.3	0.1
	Total organic matter	0.08	0.08	0.14	0.09	0.10	0.02
Ras al Zour							
	% Mortality	2	3	5	2	3	1
	Max. NH3 concentration	<1	<1	2	4	2	1
	Petroleum hydrocarbons	0.14	0.08	0.14	0.21	0.14	0.05
	Total hydrocarbons	0.39	0.24	0.35	0.55	0.38	0.11
	% Fines	0.4	0.4	0.1	0.1	0.3	0.2
	Total organic matter	0.20	0.12	0.09	0.05	0.12	0.06
Al Khiran**							
	% Mortality	2	0	0	35	9	15
	Max. NH3 concentration	<1	<1	<1	<1	<1	<1
	Petroleum hydrocarbons	0.06	0.03	0.10	65.35	16.39	28.27
	Total hydrocarbons	0.14	0.14	0.27	100.99	25.39	43.65
	% Fines	0.6	0.4	0.7	1.3	0.8	0.3
	Total organic matter	0.14	0.11	0.13	0.23	0.15	0.05
Ras al Khafji							
	A % Mortality	2	0	3	3	2	1
	Max. NH3 concentration	4	4	4	5	4	1
	B % Mortality	3	3	0	3	2	1
	Max. NH3 concentration	1	2	2	2	2	0
	Petroleum hydrocarbons	0.21	0.18	0.29	0.26	0.24	0.04
	Total hydrocarbons	0.54	0.49	0.65	0.58	0.57	0.06
	% Fines	0.1	0.1	0.1	0.2	0.1	0.0
	Total organic matter	0.02	0.02	0.02	0.02	0.02	0.00
Ras al Mishab							
	A % Mortality	2	3	2	2	2	0
	Max. NH3 concentration	4	50	40	38	33	17
	B % Mortality	3	3	0	3	2	1
	Max. NH3 concentration	1	38	26	23	22	13
	Petroleum hydrocarbons	1.38	0.03	0.08	0.22	0.43	0.55
	Total hydrocarbons	2.92	0.10	0.15	0.41	0.90	1.18
	% Fines	5.3	2.1	10.2	14.8	8.1	4.8
	Total organic matter	0.09	0.04	0.04	0.06	0.06	0.02

Table 1. Continued.

Site			Elevation * 1	2	3	4	Mean	S.D.
	A**	% Mortality	95	3	3	7	27	39
		Max. NH3 concentration	10	36	40	26	28	12
	B**	% Mortality	63	0	0	3	17	27
		Max. NH3 concentration	11	16	12	10	12	2
Ras Tanajib**		Petroleum hydrocarbons	5.56	0.00	0.00	0.00	1.39	2.41
		Total hydrocarbons	10.46	0.03	0.04	0.03	2.64	4.51
		% Fines	0.3	0.2	0.6	0.2	0.3	0.2
		Total organic matter	0.04	0.04	0.05	0.04	0.04	0.00
	A**	% Mortality	7	100	3	0	28	42
		Max. NH3 concentration	53	44	31	23	38	12
	B**	% Mortality	47	98	2	0	37	40
		Max. NH3 concentration	14	6	10	8	10	3
Manifa Bay**		Petroleum hydrocarbons	5.65	40.06	0.42	0.55	11.67	16.53
		Total hydrocarbons	15.17	61.05	0.69	0.84	19.44	24.73
		% Fines	2.5	1.7	0.6	1.2	1.5	0.7
		Total organic matter	0.07	0.07	0.03	0.04	0.05	0.02
	A**	% Mortality	55	0	3	0	15	23
		Max. NH3 concentration	9	7	11	17	11	4
	B	% Mortality	2	2	2	2	2	0
		Max. NH3 concentration	1	2	2	1	2	0
Ras al Ghar*		Petroleum hydrocarbons	8.53	4.10	1.69	0.69	3.75	3.02
		Total hydrocarbons	12.88	6.61	3.37	1.06	5.98	4.44
		% Fines	0.1	0.1	0.3	0.5	0.3	0.2
		Total organic matter	0.02	0.02	0.03	0.03	0.03	0.01
	A**	% Mortality	5	0	3	100	27	42
		Max. NH3 concentration	3	3	4	3	3	1
	B	% Mortality	3	3	0	12	5	5
		Max. NH3 concentration	2	2	3	6	3	1
Abu Ali**		Petroleum hydrocarbons	0.05	0.06	1.48	46.86	12.11	20.07
		Total hydrocarbons	0.16	0.22	2.70	73.76	19.21	31.51
		% Fines	0.0	0.1	0.1	0.6	0.2	0.2
		Total organic matter	0.01	0.01	0.02	0.04	0.02	0.01
	A	% Mortality	3	2	2	2	2	0
		Max. NH3 concentration	<1	<1	<1	3	2	1
	B	% Mortality	3	3	2	3	3	0
		Max. NH3 concentration	<1	1	<1	3	2	1
Qurrayah		Petroleum hydrocarbons	0.00	0.00	0.08	0.00	0.02	0.03
		Total hydrocarbons	0.00	0.00	0.09	0.03	0.03	0.04
		% Fines	0.1	0.1	0.1	0.2	0.1	0.0
		Total organic matter	0.03	0.03	0.01	0.01	0.02	0.01

* Elevation: 1 = high water; 2 = mid wave wash zone; 3 = 0.2 to 0.5 m water depth; 4 = 1 m water depth.

Total hydrocarbons and petroleum hydrocarbons = mg g^{1} sediment; % Fines = percentage of material smaller than 63 μm; Total organic matter = g g^{1} sediment; Ammonia = mg L^{-1}; A and B = replicate sediment samples.

** = Toxic site

Samples at Al Khiran (elevation 4), Ras Tanajib (elevation 1), Manifa Bay (elevations 1 and 2), Ras al Ghar (elevation 1), and Abu Ali (elevation 4) were significantly toxic compared to controls. In samples from other elevations at Ras al Ghar and Abu Ali, amphipods appeared languid, with their entire exoskeleton encased in oil. They were alive, and were thus counted as survivors, but they probably would not have survived much longer following the test period.

Relation of toxicity to hydrocarbon concentrations

High concentrations of petroleum hydrocarbons in the sediments of the contaminated samples caused the amphipod mortality. First, amphipod mortality was low in sediments with petroleum hydrocarbon concentrations less than 1 mg g^{-1} dry sediment, while sediments with petroleum hydrocarbon concentrations greater than 1 mg g^{-1} dry sediment were toxic (Fig. 2). Second, petroleum hydrocarbons, expressed as percentages of total hydrocarbons, were 53%-66% for toxic sediments and 35%-45% for non-toxic sediments (Table 1). Finally, toxic sites were located within the same coastal areas where heavy oil contamination was found during the spill 30 months earlier (as measured by side-looking airborne radar on 9 March 1991) (Fig. 1).

Other water quality factors including, ammonia, salinity, percent fines, and total organic matter did not contribute to amphipod mortality (Table 1). Water quality in the test jars generally stayed within the acceptable parameters for pH, temperature, dissolved oxygen, and salinity designated by the ASTM protocol, although several jars had salinities above 32‰. Ras Al Mishab, elevation 1, sample B, had an average salinity of 33.3‰ and Ras Al Mishab, elevation 4, sample B, had an average salinity of 33.5‰. High salinity in several of the test jars resulted from evaporation. However, evaporation was slow. The amphipods apparently adjusted, and there were no patterns suggesting that salinity adversely affected the amphipods in any way. The sample at Ras al Mishab, elevation 2, had the highest ammonia concentrations in the overlying water, but the percent mortality was negligible. Other samples with higher than average ammonia levels, had no corresponding amphipod mortality. Percent fines did not approach >80% in any of the samples. The sample with the greatest percentage of fines (14.8% at Ras al Mishab, elevation 4) produced no significant mortality (Table 1).

DISCUSSION AND CONCLUSIONS

Sediments from 5 out of the 11 sites sampled significantly decreased amphipod survival compared to controls. Crude oil contamination from the initial spill in January 1991 persisted for at least two and a half years at Al Khiran, Abu Ali, Ras Tanajib, Manifa Bay, and Ras al Ghar. In addition to being toxic, sediments with hydrocarbon concentrations greater than 1 mg g^{-1} have the potential to continue contaminating the sea-surface. At Manifa, oil appeared to be leaching from the beach into the water forming a broad visible surface slick extending several hundred meters from shore. In an earlier study in August 1992, oil slicks were observed leaching from the intertidal sediments and moving onto the sea-surface at Ras al Mishab and elsewhere (Hardy et al. 1993). During that survey, about half the samples of the nearshore surface microlayer were toxic to echinoderm larvae in laboratory tests (Hardy et al. 1993).

The response of *Rhepoxynius abronius* indicates, in general, how benthic organisms in the Gulf likely responded to those same sediments *in situ* (Swartz et al. 1985). However, there are reasons to believe that sediments *in situ* in the Gulf were even more toxic than the sediment samples tested in the laboratory. First, overlying water in the test jars was changed one time before the toxicity tests were initiated so that some leached oil may have been removed. Second, during the two-week waiting period prior to initiating the toxicity tests, ammonia decreased, but some petroleum probably underwent microbial degradation. Other studies suggest degradation rates for petroleum in seawater of 0.5-60 g m^{-3} d^{-1} (Atlas and Bronner 1981). Finally, in the laboratory, the toxicity of sediments to *R. abronius* were tested at 15 °C, whereas the shallow waters of the Gulf can reach temperatures as high as 33 °C. Since reaction rates can double with every 10 °C rise in temperature (Karrick 1977), *in situ* sediments may have been more toxic than laboratory tests indicated.

There were five sites that had samples with hydrocarbon concentrations over 1 mg g^{-1} dry sediment. Two sites had oil concentrated at the lowest sampling elevation, and the other three sites had oil concentrated at the highest elevations sampled. The difference is likely due to the beach morphology and sediment characteristics combined with wave activity. Exposed beaches with strong wave action generally have sediments of larger grain size which allow the oil to penetrate to a greater depth. On the other hand, wave energy increases oxidation and accelerates the degradation processes. When oil accumulates in silty or muddy sediments of calm water bays, contamination generally persists longer (NRC 1985).

The Gulf War oil spill primarily impacted intertidal communities rather than submerged plant communities (Durako et al. 1993). Several million gallons of oil remained in the subsurface of the intertidal zone one year after the spill, with a 15-20 cm average penetration depth on exposed sandy beaches (Hayes et al. 1993). Because of the unusually great depth of penetration and the amount of oil remaining in the subsurface habitats, oil contamination will likely remain for many years and possibly decades (Hayes et al. 1993). A marine sanctuary, recently created north of Jubail, Saudi Arabia, includes about 400 km of coastline and five coral islands (Krupp and Jones 1993). Sediment toxicity was found at several sites within this region.

In summary, the results indicate that 30 months after the oil spill: 1) Petroleum concentrations >1 mg g^{-1} dry sediment remained nearshore at Al Khiran, Kuwait, and at four other sites sampled between Ras Tanajib and Abu Ali, Saudi Arabia; 2) These contaminated sediments were potentially toxic to the local benthic infauna as shown by amphipod toxicity tests; and 3) Visual observations and high concentrations of petroleum hydrocarbons in the oiled sediments revealed a high potential for continued contamination of the nearshore area including the sea-surface microlayer.

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